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Water Quality Evolution of the Upper Cretaceous to Recent Aquifers in Jordan

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Abstract

Two main porous and permeable rock sequences of Upper Cretaceous to recent ages build the near-surface aquifer systems in Jordan; the lower aquifer system of the combined Massive Limestone and Silicified Limestone composite aquifer (B2/A7) and the Chalk Marl, basalt, and recent deposits upper aquifer system (B4,5, and recent deposits). The thick Bituminous Marl Formation (B3) separates these two aquifer systems. Both aquifers receive recharge along their outcrops, resulting in fresh groundwater with low salinity. Where the Bituminous Marls confine the lower aquifer system in the Plateau area, its groundwater increases in salinity and temperature and becomes subject to reducing conditions, which is reflected in its quality. In the upper aquifer system of the Azraq, Hammad, and central Jafr areas, evaporites originating from recent playa sediments affect the fresh recharge groundwater quality, and its originally low-salinity carbonate groundwater becomes rich in chlorides and sulfates. In areas of erosion with no playas and evaporites, the water quality remains fresh and reflects water interaction with the aquifer rock matrix. In this article, the conditions and sources of increasing salinity parameters, lower pH values, higher temperatures, and H2S, concentrations in the Lower groundwater system are discussed. In addition, this article will clarify the effects of playas and mudflats on the quality of the groundwater in some areas of the surficial aquifer that do not affect other areas of the same aquifer. This study shows that the hydrogeochemical evolution of the lower groundwater systems, A7/B2, indicates that their overexploitation will lead to a reduction in the freshwater discharges from springs and seepages and to the enhancement of groundwater reactions with the confining bituminous marls, accompanied by releases of CO_2 and HS gases into the groundwater of the lower aquifer. In the surficial aquifer affected by playas and mudflats, the result will be increased groundwater salinity because of the mobilization of sulfate- and chloride-rich water from the playa sediments into the fresh groundwater regimes. Therefore, great attention must be given before any decision is made to overexploit these aquifers.

Keywords

Natural Groundwater Qualities, Evolution, Threats of Overexploitation, Surficial, Tertiary, Upper Cretaceous Aquifers, Mobilization of Salts

1. Introduction

The greater part of Jordan's near-surface geology consists of Upper Cretaceous, Tertiary, volcanic, and Quaternary rocks (Bender, 1968; Bandel & Salameh, 2013). These rocks contain the country's main renewable fresh groundwater bodies and serve as a major source of the water supply. The original quality of the groundwater (not much affected by human activities) differs from one aquifer subarea to another, as affected by the constellation of aquifers in these subareas, their mineral composition, recharge, flow, and discharge mechanisms, and water-rock and water-water interactions.

The current article discusses the evolution of the natural water qualities in the different Upper Cretaceous to recent rock formations in the highlands of Jordan to work out the natural conditions and mechanisms leading to the evolution of their water compositions.

The study illustrates the dangers of additional groundwater extraction from different aquifer systems on their safe yield (continuous drop of groundwater levels) and quality deterioration. Over-pumping will lead to the mobilization of evaporates found in areas in the surroundings of surficial playa deposits, such as the Azraq, Hammad, and Central Jafr areas. In addition, in areas where the bituminous marls confine the lower aquifer system (B2/A7), increases in groundwater salinity, CO_2 and HS gases, and temperature lead to enhanced releases of trace elements from the confining bituminous rocks and to groundwater quality deterioration.

Previous Work

A large number of groundwater analyses exist in the archives of the Ministry of Water and Irrigation (MWI, 2016) and serve as monitoring data to control the water quality in the aquifers and to guarantee a safe water supply for the inhabitants. Many M.Sc. and Ph.D. theses carried out under the authors' supervision, in addition to published research works containing detailed analyses of the groundwater in specific areas of the country, will also be used in this study as important sources of information. Such information is taken from: Salameh et al., 2024; Brückner et al., 2021; Goode, 2021; MWI & BGR, 2019; Salameh et al., 2018; Salameh & Tarawneh, 2017; Tarawneh & Salameh, 2016; Abu Zahra, 2012; Ibrahim, 2012; Al-Sawarieh, 2005; Salameh & Hammuri, 2008; Salameh, 2001; El-Nasser, 1991; Rimawi, 1985; Rimawi & Udluft, 1985; and many others. These works concentrated on specific areas and discussed the existing status of groundwater quality. In Jordan, only a few studies have tried to explain the evolution of the natural groundwater composition (Rimawi, 1985; Salameh & Hammuri, 2008; Salameh, 2001; Salameh et al., 2024; Salameh et al., 2017).

This study aims to explain the natural evolution of the different water qualities in the Upper Cretaceous to recent aquifers, because of water-rock and water-water interactions, in order to understand the mechanisms leading to the formation of the different water qualities. It also aims to reach recommendations for the sustainable management of the aquifers and to limit their deterioration by the mobilization of salts contained in the surrounding rock formations.

2. Methodology

The water quality analyses for the different aquifers are the results of the author's work throughout the last four decades. In addition, analyses were taken from the archives of the Ministry of Water and Irrigation (MWI, 2016). Information from the author's supervised Ph.D. and M.Sc. theses has also been consulted. **Table 1** lists the techniques used in the analyses. Most relevant to the study are samples collected during pre-development eras of industrial, agricultural and urban activities, which better account for the natural groundwater systems. For that hundreds of samples were revisited and the most reliable ones of them were used in the study.

Table 1. Analytical techniques used in measuring the various water parameters.

Parameter	Analytical method
Temperature (˚C)	Field thermometer WTW instrument, 0.1˚C accuracy
pH-Value	Field pH-meter WTW instrument
Electrical Conductivity EC (μS/cm)	Field EC-meter WTW instrument
Sodium (Na^+)	These elements were measured by using a flame photometer
Potassium (K^+)	
Sulfate (SO_4^{2-})	These elements were measured by using a spectrophotometer
Nitrate (NO_3^-)	
Chloride (Cl^-)	Titration, using 0.1 n HCI and Phenonaphthaline indicator
Calcium (Ca^{2+})	Titration, using 0.1 n HCI and Phenonaphthaline indicator
Magnesium (Mg^{2+})	Titration, using 0.1 n HCI and Phenonaphthaline indicator
Carbonate (CO_3^{2-})	Titration, using 0.1 n HCI and Phenonaphthaline indicator
Bicarbonate (HCO_3^-)	Titration, using 0.1 n HCI and Bromocrysol indicator
Trace elements	Atomic absorption
H_2S	WTW-Field kits

AquaChem Software was used to produce Piper, Schöller, and Durov diagrams, calculate saturation indices, and conduct correlation analyses.

3. Geology and Hydrogeology of the Study Area

Overlying the deep sandstone aquifer complex consisting of clastics of Precambrian through Lower Cretaceous ages, with missing Devonian, Carboniferous, and Early Permian, are rocks of Upper Cretaceous, Tertiary, and Quaternary ages, together composing the geologic column of Jordan. Bender, 1968; NRA, 2016 (**Table 2**); Salameh et al. (2024) discussed the quality of the deep clastic aquifer groundwaters and its evolution in different areas of the country (Salameh et al., 2024), whereas the current study discusses the water quality evolution in the Upper Cretaceous, Tertiary, and recent rocks building surficial or near ground surface aquifers. **Figure 1** gives the study sites' locations in Jordan and **Figure 2** illustrates the outcropping hydrogeological formations.

Table 2. The geologic column in the study area (NRA, 2016).

Formation age	Formation name	Type of rocks	Thickness (m)	Main hydraulic characteristics	General consideration
Surficial recent deposits	Recent	Recent gravel, sand, and silt	Up to 50 m	Local aquifer when conditions allow	Irrelevant as a source of water
Basalts	Basalts	Basalts	Up to several 100 m	Important aquifer in central N Jordan	Good to excellent Aquifer, widely exploited
Late Miocene	Qirma B6	Sandstone and siltstone	Up to 40 m	Empty aquifer, only in Azraq area	Irrelevant as a source of water
Eocene	Chalk Marl B4,5	Chalk marl and chert	Up to 170 m	Local surficial aquifer	A relevant local water supply source
Cretaceous-Tertiary	Bituminous Marl B3	Bituminous Marl	200 - >800 m	Aquiclude	Aquiclude
Campanian Maastrichtian	Um Ghudran and Silicified limestone B1/2	Silicified limestone is overlain by beds of phosphatic chert	Around 70 m	Excellent aquifer	Good to excellent Aquifer, widely exploited
Turonian-Santonian	Massive Limestone A7	Massive sandy limestone	55 m	Good aquifer	
Cenomanian,	Shueib A5/6, Hummar A4, Fuheis A3, Na'ur A1/2	Alternating beds of limestone, dolomite, marly limestone, dolomitic limestone, sandstone, marl and some gypsum layers and evaporate residues	Around 300 m	Poorly developed aquifer. In many areas' springs issued from the limestone and dolomite beds	In general, poorly developed aquifer with some good yield aquifer layers. On a regional scale, it leaks water down into the older aquifers
Deep sandstone aquifer system	Precambrian through Lower Cretaceous	Coarse, medium and fine-grained sandstone	1450 - 1600 m	Good aquifer	Good to excellent aquifer directly overlying the granitic basement

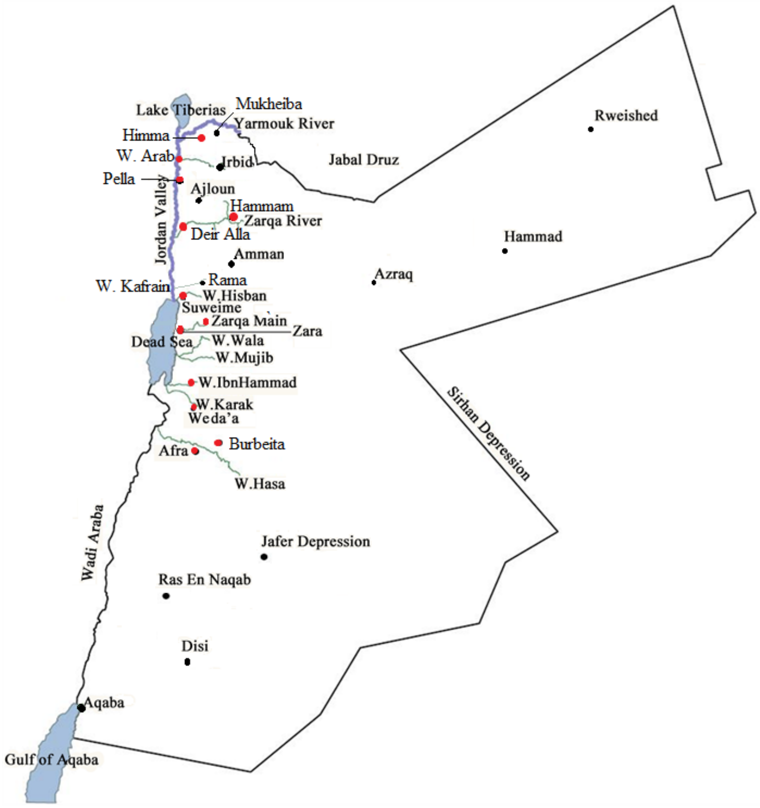


Figure 1. Location map showing the different areas related to sites mentioned in this work (Source: Author).

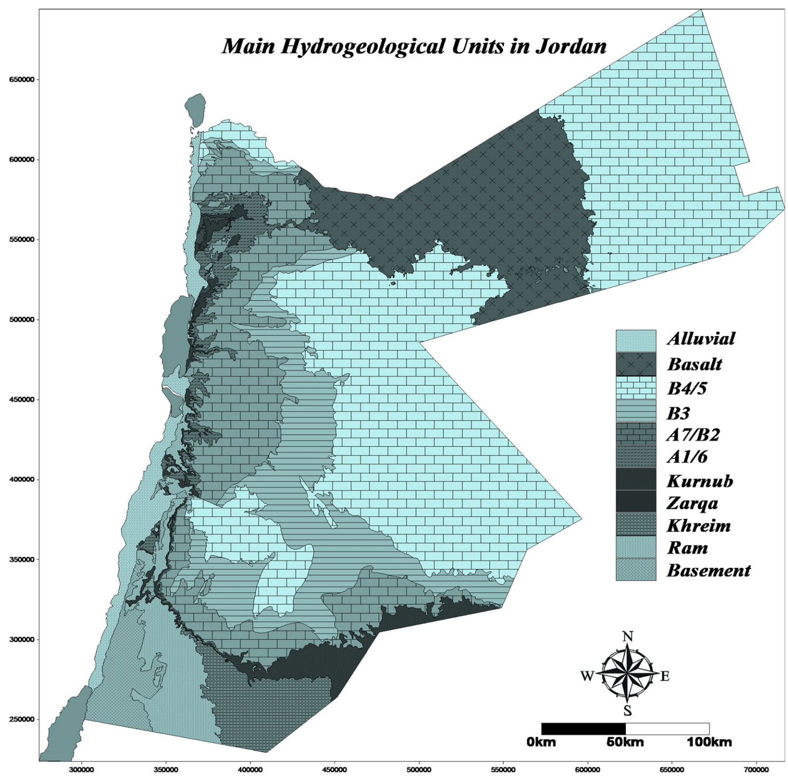


Figure 2. Main hydrogeological formations in Jordan (NRA, 2016).

3.1. Rock Sequence I: Upper Cretaceous Aquifer/Aquiclude Series of Nodular and Echinoidal Limestone Formations (Na'ur, Fuheis, Hummar, and Shueib Formations, A1-6)

This series of rocks (A1-6) comprises limestone, dolomite, marl, chalk, and shale beds of more than 300 m thick (Table 2, Figure 2). It overlies the deep sandstone aquifer system composed of Lower Cretaceous to Precambrian clastic sediments, which in turn overlies the Precambrian granitic basement. The series contains thick beds of fractured and karstified limestone building local aquifers, such as the Hummar Formation (A4) or the limestone beds forming parts of the Na'ur and Fuheis Formations (A1-3). The series, as a whole, forms a poorly developed aquifer, but on a regional scale, it hydraulically connects the overlying aquifers (Massive Limestone and the Silicified Limestone (A7/B2)) with the underlying deep sandstone aquifer complex (Lower Cretaceous and older clastic rocks). The series contains, locally, gypsum layers of up to a few meters in thickness in addition to thin gypsum layers and patches within the clay layers. Other evaporite residues are also found in the rock series.

3.2. Rock Sequence II: Massive Limestone and Silicified Limestone Aquifer System (Wadi Sir, Um Ghudran, and Amman Formations (A7/B1,2))

This sequence consists of a series of thick, massive limestone beds overlain by phosphate rocks and cherts with a total thickness of 200 - 300 m, possessing very high porosity and permeability. In some areas, the B2 Formation is separated from the A7 Formation by the Um Ghudran Formation (B1), a very poor aquifer, which has a thickness of 0 - 35 m (Table 2). The rock series covers extensive areas along the high mountains of Jordan, extending from the Ras en Naqab area in the south to Jordan's borders with Syria in the north and from the eastern escarpment of the Jordan Rift Valley area in the west, eastwards beyond Jordan's borders. In the eastern plateau area, a thick aquiclude, the Bituminous Marl Formation (B3), overlies the A7/B2 and confines its groundwater (Figure 2).

3.3. Rock Sequence III: Bituminous Marl Aquiclude (Muwaqqar Formation, B3)

The Muwaqqar Bituminous Marl Formation (B3) of late Upper Cretaceous–early Tertiary age crops out extensively along the Plateau area of Jordan. It forms a major aquiclude separating the surficial aquifers (B4,5,6, the recent basalts, and Quaternary sediments) from the Upper Cretaceous aquifers (A7/B2). The B3 confines the underlying aquifer systems (Figure 2, Table 2) and is generally overlain by chalk marls of Paleocene to Eocene age, which, together with recent basalts and sediments, form a surficial aquifer.

To the north of the northern latitude of the Dead Sea to around 25 km south of the Yarmouk River, the Bituminous Marls have been eroded and are only found in patches. The formation builds an aquitard of up to 300 m thickness, and in Jafr Depression, it even reaches around 800 m (Bender, 1968; NRA, 2016).

3.4. Rock Sequence IV: The Surficial Aquifer System: The Chalk Marl Formations; B4,5 (Rijam and Shallala) and the Sandstone Formation; B6 (Um Qirma in the Azraq Area), the Basalt Aquifer, and the Recent Sediments of the Highlands (NRA, 2016)

The Rijam and Shallala (B4,5) Formations consist of marl and chalk beds with some thin chert beds, generally less than 20 cm in thickness. They cover large parts of the highlands of Jordan to the east of the Jordan Rift Valley Shoulder Mountains, overlying the thick aquiclude of the Bituminous Marl Formation (Figure 2, Table 2). In the Azraq area and its surroundings, the Um Qirma Formation (B6) overlies, in places, the Shallala and Rijam Formations. The B6 consists mainly of sandstone and siltstone, generally about 40 m thick, and contains no water. Rijam and Shallala form Jordan's local surficial aquifers and receive direct recharge from precipitation and flood flow water along their outcrops. In some areas, such as Azraq, Mafraq, and partly Jafr, this formation is found covered by basalts and/or recent sediments.

The B4,5 Formations cover five main areas in Jordan: Jafr, Sirhan, Hammad, Azraq, and Yarmouk (NW of Irbid). Recent, mainly alluvial, sediments of Quaternary age cover the B4,5 and the basalts, in places, forming local surficial aquifers.

4. Hydrochemistry Results and Discussion

4.1. Rock Sequence I: Upper Cretaceous Aquifer/Aquiclude Series of Nodular and Echinoidal Limestone Formations (Na'ur, Fuheis, Hummar and Shueib Formations, A1-6)

The Upper Cretaceous aquifer consists of argillaceous limestone. This poorly developed aquifer receives very limited amounts of direct recharge from precipitation or flood flows. Its groundwater originates from the downward percolation of groundwater in the overlying aquifers, mainly from the A7/B2 aquifer. Due to the presence of evaporite residues in Formations A1-3 and A5, 6, the salinity of the groundwater increases as a function of water residence time and, hence, interaction with the aquifer matrix, recharge/discharge mechanisms, and location relative to the evaporite residues concentrations within the rock formation. Therefore, the composition of the groundwater varies between that of the overlying A7/B2 aquifer, the source water, and water affected by evaporites. The A7/B2 groundwater is directly or indirectly (along wadis) recharged by precipitation water and its chemistry reflects its reaction with the carbonates rock sequence. But once it percolates into the underlying evaporates-containing poor aquifer sieries, the B1-6, its water chemistry changes radically to chloride-sulfate water.

Table 3(a) lists some of the analyses of the groundwater in the A1-A6 with their salinities, which range from about 845 to about 1210 μS/cm. In the Piper diagram (Figure 3(a)), the water of this group plots within the earth's alkaline type with no dominant cations but is very close to sulfate and chloride waters. In the Durov diagram (Figure 3(b)), the water plots in the dissolution/mixing regime, but the geology, recharge, and discharge mechanism of the groundwater suggest dissolution of the rock matrix rather than mixing with other groundwater types, with $Ca^{2+} \sim Mg^{2+} \sim Na^{+} > K^{+}$ and $HCO_3^{-} > Cl^{-} > SO_4^{2-}$. Figure 3(c) shows the Schöller diagram in the Na'ur, Fuheis, Hummar, and Shueib Formations, A1-6. The scattering of the composition in the different diagrams reflects the spatial distribution of evaporates within the rock formations.

Table 3. (a) Composition of the A1-6 sampled water sources (EC in μS/cm; concentrations in meq/l); (b) Correlation matrix for the normal water component of in Na'ur, Fuheis, Hummar, and Shueib Formations, A1-6; (c) Saturation Indices (SI) of the main minerals in Na'ur, Fuheis, Hummar, and Shueib Formations, A1-6.

(a)

Sampling site	EC	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}
Abu Hamed Sp.	1200	8.35	3.2	5.1	4.2	0.34	4.0	1.9	6.2
Abu Nusseir	845	7.35	3.16	3.26	3.07	0.09	2.83	2.33	3.96
Na'ur Road w.	1200	7.9	4.00	4.22	4.35	0.20	4.24	4.52	3.90
Gheith, S64	1390	7.40	3.7	3.98	5.55	0.26	6.16	3.45	4.28
Ifjeij Sp.	1410	7.28	3.12	2.4	5.50	0.12	7.50	3.00	3.90
Eljheilyya Sp.	1600	7.70	5.12	3.65	3.60	0.07	3.28	3.47	6.15
Liweinat Sp.	1100	8.10	3.10	5.30	3.45	0.40	3.60	3.85	4.60

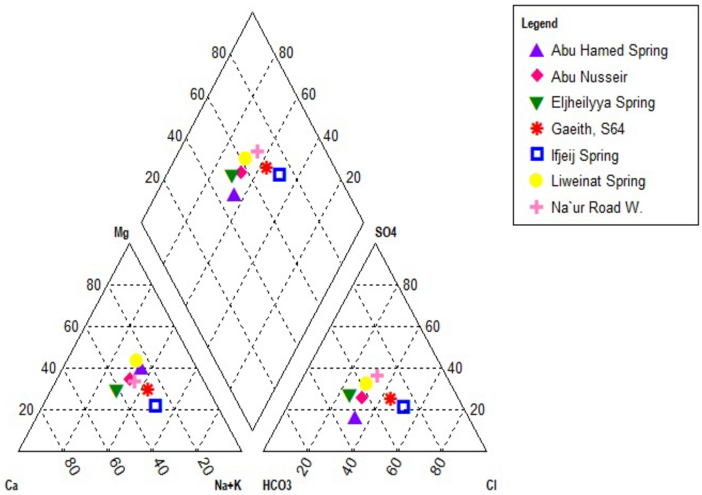
(b)

	EC	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-1}	SO_4^{2-}	HCO_3^{-}
EC	1								
pH	0.552981	1							
Ca^{2+}	0.780115	0.486857	1						
Mg^{2+}	−0.39036	−0.04303	−0.22778	1					
Na^{+}	0.856316	0.593329	0.610659	−0.54831	1				
K^{+}	0.631627	0.83082	0.644075	−0.00908	0.736711	1			
Cl^{-}	0.231693	−0.28581	0.364169	0.220897	0.144166	0.156587	1		
SO_4^{2-}	0.28637	−0.02791	0.589114	0.415538	0.076671	0.308469	0.775458	1	
HCO_3^{-}	−0.45973	−0.27563	−0.62179	0.480957	−0.69083	−0.60384	−0.32596	−0.37957	1

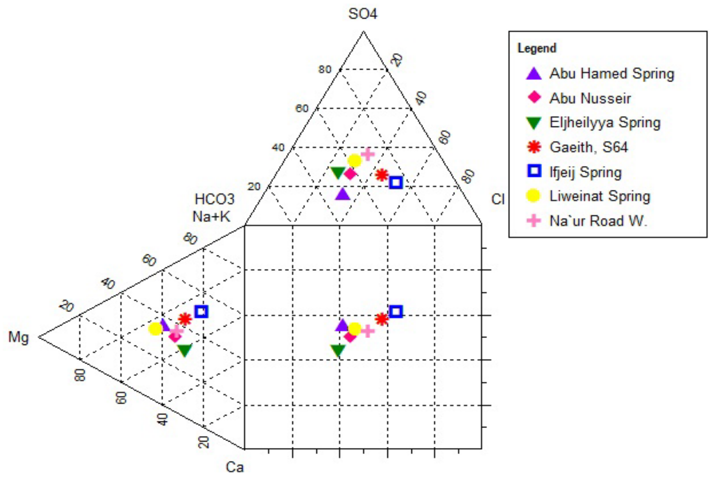
(c)

Sampling site	Anhydrite	Aragonite	Calcite	Dolomite	Gypsum	Halite
Abu Hamed Sp.	−2.0628	0.9837	1.1275	2.5976	−1.843	−6.4685
Abu Nusseir	−1.913	−0.2159	−0.0685	−0.0567	−1.6759	−6.7317
Na'ur Road w.	−1.6018	0.3688	0.5162	1.1227	−1.3648	−6.4188
Gheith, S64	−1.7438	−1.7438	0.0389	0.1766	−1.5069	−6.1522
Ifjeij Sp.	−1.8359	−0.3253	−0.1779	−0.4029	−1.5989	−6.0657
Eljheilyya Sp.	−1.6089	0.4824	0.6298	1.1808	−1.3719	−6.6121
Liweinat Sp.	−1.7777	0.5298	0.6772	1.6563	−1.5989	−6.0657

(a) Sp.: Spring.



(a)



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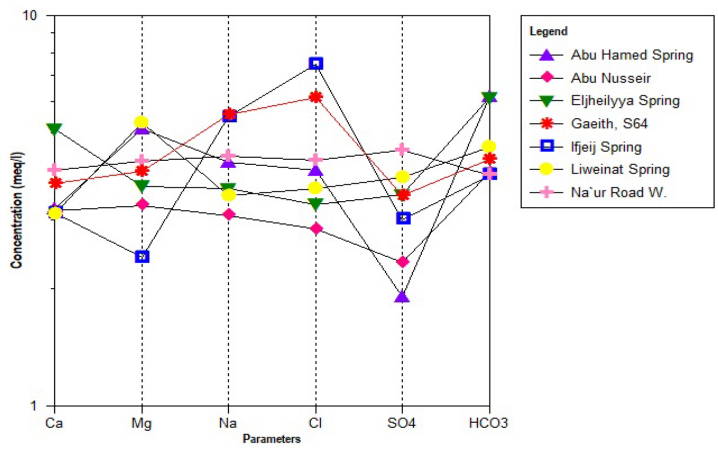


(c)

Figure 3. (a) The Piper diagram of the water within the Na'ur, Fuheis, Hummar, and Shueib Formations, A1-6; (b) The Durov diagram shows the water plots in Na'ur, Fuheis, Hummar, and Shueib Formations, A1-6; (c) The Schoeller diagram shows the water Quality in Na'ur, Fuheis, Hummar, and Shueib Formations, A1-6.

The Na^+/Cl^- and $Ca^{2+} + Mg^{2+}/HCO_3^- + SO_4^{2-}$ equivalent ratios are around unity , indicating the dissolution of the aquifer matrix containing evaporates, without ion exchange reactions. The correlation of the different parameters is very weak, reflecting the variability of the aquifer composition and its rapid change in space (**Table 3(b)**). The water in these rocks is slightly under-saturated with respect to calcite, dolomite, aragonite, and anhydrite, intermediately unsaturated with respect to gypsum, and strongly unsaturated with respect to halite (**Table 3(c)**).

Due to the low permeability of this sequence and hence the long residence time of the groundwater in the rocks, and due to its evaporate contents, the groundwater shows an increase in salt contents compared to the source water.

4.2. Rock Sequence II: Massive Limestone and Silicified Limestone Aquifer System (Wadi Sir, Um Ghudran, and Amman Formations, A7/B1, 2)

This sequence is the most important source of renewable groundwater in Jordan. Its water originates mainly from direct recharge along the extensive outcrops along the western highlands. Due to the composition of the aquifer, consisting of limestone and chert, and its long exposure to flushing by rainwater, its water is fresh and generally suitable for common use purposes.

The groundwater in this aquifer flows in two directions from its recharge area along the high mountains: to the west towards the Jordan Rift Valley, where it discharges from mountain springs, and eastwards, building a groundwater body underlying the Plateau area, where the thick Bituminous Marls (B3) confine it. This flow mechanism and its governing conditions entail different groundwater qualities; therefore, the two parts of the groundwater flow in the aquifer will be discussed separately.

4.2.1. Mountain Springs

Springs discharging from this rock sequence issue along the side wadis of the Jordan Rift Valley, extending from the Ras en Naqab area in the south to the Ajlun area in the north. Examples of the water quality are listed in **Table 4(a)**, and their plots in Piper, Durov, and Schöller diagrams are in (**Figures 4(a)-(c)**).

The salinity of the groundwater is relatively low and ranges from around 500 to about 950 μS/cm. Water-rock interactions are restricted in time by the relatively fast recharge-discharge duration of around one year and by the mineralogical composition of the well-flushed composite aquifer of highly lithified chert, limestone, dolomite, and phosphate rocks.

In the Piper diagram (**Figure 4(a)**), the water plots in the earth alkaline type to earth alkaline type with increased portions of alkalis and prevailing carbonates. In the Durov diagram (**Figure 4(b)**), the water plots on the dissolution-evaporation line with no ion exchange processes between the water and the aquifer matrix. In the Schöller diagram, **Figure 4(c)**, the ionic ratios are Ca > Mg >< Na and HCO_3 > Cl > SO_4. Worth mentioning here is that Salt and Hizzir springs are polluted by household wastewater as indicated by their high nitrate contents and hence their different plots in the diagrams.

Correlations are clear between Ca, K, and SO_4, Na and Cl, K and NO_3; the latter indicates domestic waste pollution (Table 4(b)).

Table 4. (a) Composition of spring water issuing from the Massive Limestone/Silicified Limestone (B2/A7) composite aquifer along the highlands of Jordan (EC μS/cm, and all others in meq/l); (b) Correlation matrix for spring water issuing from the Massive Limestone/Silicified Limestone (B2/A7) composite aquifer along the highlands of Jordan; (c) Saturation Indices (SI) for spring water issuing from the Massive Limestone/Silicified Limestone (B2/A7) composite aquifer along the highlands of Jordan.

(a)

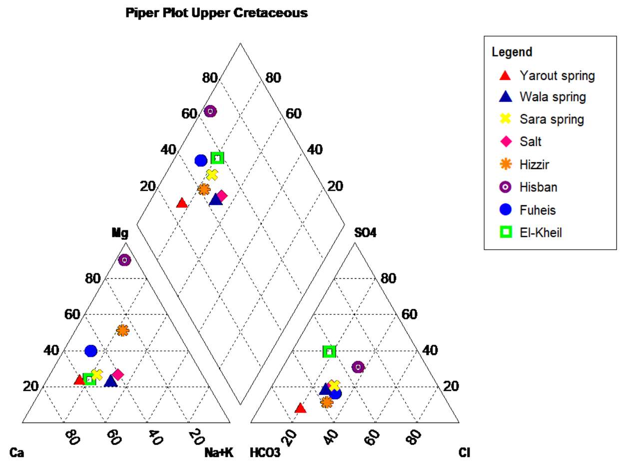
Spring name	EC	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^-	NO_3^-
Yarout sp.	640.0	7.7	4.1	1.6	1.0	0.1	1.3	0.5	4.6	0.4
Sara spring	880.0	7.6	4.1	2.1	1.4	0.4	2.1	1.4	3.5	0.8
Wala spring	494.0	1.7	2.4	1.2	1.5	0.2	1.4	0.9	2.8	0.1
El-Keil	630.0	7.4	3.6	1.5	1.2	0.1	1.6	0.3	3.9	0.6
Hisban	999	7.65	4.18	3.40	3.78	0.2	4.20	3.50	3.82	0.44
Fuheis	540	6.78	2,46	2.05	0.66	0.03	1.58	0.78	2.51	0.21
Salt	930	6.50	4.51	2.78	1.82	0.46	2.17	1.53	3.92	1.92

(b)

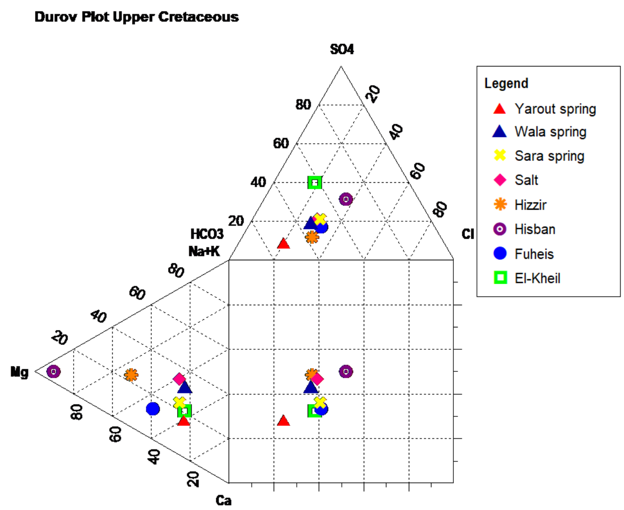
	EC	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	NO_3
EC	1									
pH	0.527632	1								
Ca	0.606973	0.514031	1							
Mg	0.720432	0.376017	−0.03933	1						
Na	0.70382	0.115685	0.387717	0.487604	1					
K	0.502447	0.00295	0.134091	0.436646	−0.06538	1				
Cl	0.793692	0.345891	0.333145	0.66148	0.938006	−0.00691	1			
SO_4	0.71256	0.156319	0.42209	0.439976	0.933915	−0.03487	0.928173	1		
HCO_3	0.476121	0.551331	0.444969	0.433332	0.198636	0.213472	0.192291	−0.005	1	
NO_3	0.636286	0.286771	0.455324	0.496296	0.106836	0.764226	0.158598	0.081176	0.45564	1

(c)

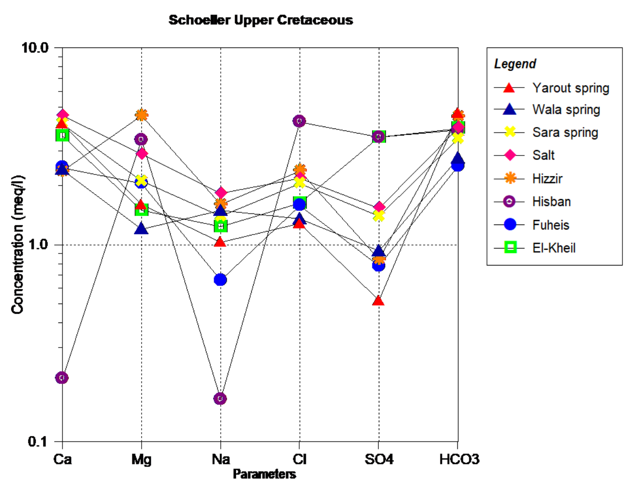
Spring name	Anhydrite	Aragonite	Calcite	Dolomite	Gypsum	Halite
Yarout sp.	−2.3667	0.5096	0.6477	1.1036	−2.1841	−7.5733
Sara spring	−2.0091	0.1647	0.3085	0.4587	−1.7893	−7.2299
Wala spring	−2.3105	−0.3907	−0.2426	−0.7336	−2.0705	−7.3439
El-Keil	−1.678	−0.1508	−0.0027	−0.3317	−1.4381	−7.3695
Hisban	−1.6686	0.2192	0.3629	0.7654	−1.4488	−6.4949
Fuheis	−2.384	−0.9495	−0.8058	−1.5598	−2.164	−7.6454
Salt	−1.9771	−0.8611	−0.7173	−1.5124	−1.7574	−7.1008



(a)



(b)



(c)

Figure 4. (a) The Piper diagram for the water in the B2/A7 Mountain springs in Jordan; (b) The Durov diagram for the water in in the B2/A7 Mountain springs in Jordan; (c) The Schöller diagram for the water in the B2/A7 Mountain springs in Jordan.

The water of these springs is ±saturated with aragonite, calcite, and dolomite, under-saturated with gypsum and anhydrite, and strongly under-saturated with halite (**Table 4(c)**).

4.2.2. B2/A7 Underlying the Plateau Area (Plateau Groundwater)

The recharge water in the Massive Limestone and Silicified Limestone aquifer system (A7/B2) that flows eastwards underground in the Plateau area becomes, at a distance of 20 - 30 km east of the mountains, gradually confined by the Bituminous Marl (B3) aquiclude. Due to long flow times and hence long water-rock interactions, and due to the confinement by the Bituminous Marl aquiclude, the groundwater gains salinity, which increases to more than 1000 µS/cm (**Table 5(a)**), and temperature, which rises to more than 40˚C (Sawarieh, 2005). In addition, the groundwater in most wells has an HS smell, and contains high CO_2 gas concentrations because of microbial sulfate reduction within the confined parts of the aquifer.

The water composition plots in the Piper diagram as earth alkaline type with increased alkalis and prevailing chlorides. In the Durov diagram, the water plots on the dissolution/evaporation line with increased dissolution of the calcareous rock matrices compared with the springs' water in the west. In the Schöller diagram, the water shows Na ~ Ca > Mg and Cl ~ HCO_3 > SO_4 (**Figures 5(a)-(c)**). The water is ± saturated with calcite, dolomite, and aragonite, under-saturated with gypsum and anhydrite, and strongly under-saturated with halite (**Table 5(b)**, **Table 5(c)**).

Table 5(b) shows high correlations between Ca, Na, and SO_4, Na and Cl, and Cl and SO_4, which indicates the dissolution of the aquifer matrix. All of the above indicates recharge water, which has reacted with a calcareous rock matrix and become confined under reducing environments.

Table 5. (a) Composition of groundwater in the Massive Limestone/Silicified Limestone (B2/A7) composite aquifer underlying the Plateau area of Jordan (EC µS/cm, NO_3 in mg/ land, others in meq/l); (b) Correlation matrix groundwater in the Massive Limestone/Silicified Limestone (B2/A7) composite aquifer underlying the Plateau area of Jordan; (c) Saturation Indices of groundwater in the Massive Limestone/Silicified Limestone (B2/A7) composite underlying the Plateau area of Jordan.

(a)

Name/	Code	EC	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	NO_3^{-}
Qatraneh	CD 1001	1200	7.9	4.35	3.08	4.65	0.12	5.09	1.96	5.08	0
Swaqah	CD 1009	1080	7.7	4.0	2.50	3.09	0.06	4.11	1.60	5.13	2
Al-Abeid	CD1007	910	7.3	3.80	2.78	3.17	2.3	3.29	1.69	4.63	2.3
Al-Waleh	CD1016	970	7.2	4.1	3.00	2.78	0.06	2.89	1.81	5.19	2.1
	CD1072	650	7.3	3.45	1.75	1.70	0.05	1.63	0.77	4.00	21
	CD1377	1065	7.49	4.29	1.75	3.72	2.53	3.27	1.85	5.58	0
Al-Kastal	CD1010	1440	7.39	5.44	3.34	5.51	0.81	7.15	2.72	4.35	6.7
	CD3075	1138	7.37	5.85	1.17	4.61	0.20	4.59	3,60	3.50	3
	F1307	1986	7.35	9.50	3.58	6.00	0.30	8.34	5.59	4.90	1.2

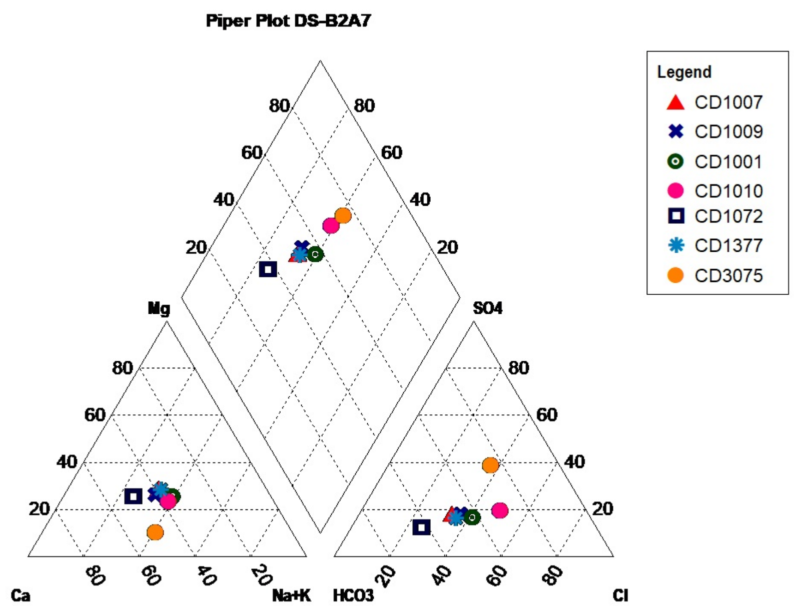
Continued

(b)

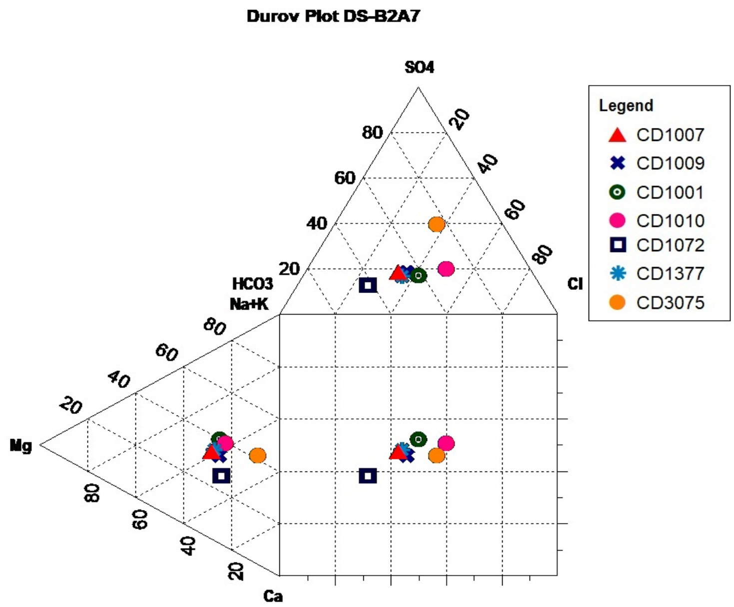
	EC	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	NO_3^{-}
EC	1									
pH	0.086762	1								
Ca^{2+}	0.92675	−0.14493	1							
Mg^{2+}	0.592245	0.087022	0.378997	1						
Na^{+}	0.908438	0.196897	0.799215	0.452276	1					
K^{+}	−0.12719	−0.14517	−0.18853	−0.11844	−0.02602	1				
Cl^{-}	0.961119	0.154482	0.845495	0.610923	0.949832	−0.15814	1			
SO_4^{2-}	0.908304	−0.14014	0.981039	0.319378	0.835043	−0.15638	0.840449	1		
HCO_3^{-}	0.137629	0.347086	−0.08663	0.42325	−0.02416	0.311507	0.001107	−0.13427	1	
NO_3^{-}	−0.45504	−0.34807	−0.27891	−0.30093	−0.50595	−0.2747	−0.39308	−0.38599	−0.54788	1

(c)

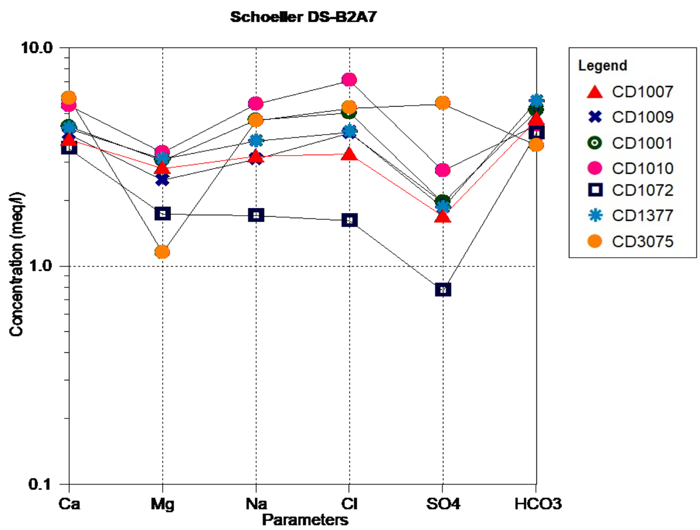
	SI	Anhydrite	Aragonite	Calcite	Dolomite	Gypsum	Halite
DS-B2A7	CD 1001	−1.885	−0.2597	−0.1083	−0.3812	−1.6372	−6.2986
	CD 1009	−1.8951	0.2729	0.4238	0.64	−1.647	−6.5641
	CD1007	−1.9727	−0.1844	0.0332	−0.2062	−1.7236	−6.6465
	CD1072	−2.2914	−0.251	−0.8199	−0.5074	−2.0423	−7.2121
	CD1377	−1.9114	0.1286	0.2798	0.412	−1.6623	−6.4808
	CD1010	−1.6891	−0.0125	0.1388	0.0549	−1.4402	−6.0859
	CD3075	−1.3443	−0.1124	0.0388	−0.6337	−1.0953	−6.2874



(a)



(b)



(c)

Figure 5. (a) The Piper diagram for the water in the B2/A7 Plateau area; (b) The Durov diagram for the water in in the B2/A7 Plateau area; (c) The Schöller diagram for the water in the B2/A7 Plateau area.

4.3. Rock Sequence III: Bituminous Marl Aquiclude (Muwaqqar Formation, B3) Bitumen

Its primary porosity is very low, less than 10^{-7} m/s. In some areas, it possesses secondary permeability, allowing for hydraulic interconnections of the overlying and underlying aquifers' groundwater. No springs or wells are producing from this aquiclude, but it has quality impacts on overlying and underlying aquifers due to its bitumen contents and its confinement of the underlying groundwater bodies.

4.4. Rock Sequence IV: The Surficial Aquifer System: The Chalk Marl Formations; B4,5 (Rijam and Shallala), the Sandstone Formation; B6 (Um Qirma in the Azraq Area), the Basalt Aquifer, and the Recent Sediments of the Highlands

This Chalk Marl Formations (B4,5) aquifer crops out in five main areas in Jordan, namely Jafr, Sirhan, Hammad, Azraq, and Yarmouk (NW of Irbid) (Figure 1), where the thick aquiclude of the Bituminous Marl Formation (B3) underlies them. Only in the Azraq Depression does the Um Qirma Formation (B6), consisting of sandstone, chalk, and chert nodules, cover small areas of the B5 with a thickness generally up to 40 m. The B6 Formation does not contain groundwater bodies.

Recent basalts of Harrat esh Sham and recent alluvial deposits cover the B4/B5 Formations in parts of the Hammad and Azraq areas, which results in the groundwater there having different hydrochemistry compared to the Jafr, Sirhan, and Yarmouk areas.

The groundwater in this composite aquifer is generally fresh, except in playa and mudflat environments, where evaporation has left behind salty grounds so that the groundwater in the surroundings becomes slightly brackish (Table 6). Therefore, due to the direct effects of differences in climatic conditions, topographic constellations, and geologic settings on this surficial aquifer, its water quality in different parts of the country differs. Hence, its quality evolution will be considered for each area separately.

Table 6. (a) Analytical results of the major constituents of the composite B4,5, basalt, and recent sediments groundwater sources (EC in μS/cm; NO_3 in mg/l, other concentrations in meq/l); (b) Correlation matrix of the major constituents of the composite B4,5, basalt, and recent sediments groundwater sources; (c) Saturation Indices (SI) for the major constituents of the composite B4,5, basalt, and recent sediments groundwater sources/

(a)

Area/Well Name/Code		EC	pH	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-	NO_3
Yarmouk	AD1208	1420	7.7	4.90	2.75	6.52	0.15	6.94	3.46	3.39	50.0
Azraq (B5)	F1274	1770	7.5	6.30	3.58	8.00	0.125	8.86	4.21	4.73	3.2
	F1045	1290	8.0	3.05	3.08	6.34	0.275	7.34	3.10	2.16	0.0
	F1013	1770	7.5	4.50	3.42	9.70	0.175	8.97	5.90	2.77	0.0
Jafr	G1280	1200	7.4	4.85	4.50	3.35	0.025	5.47	1.49	5.52	0.1
	G1276	1034	7.8	3.25	2.75	4.48	0.075	4.69	1.94	3.89	3.0
	GL004	1150	7.4	3.90	3.33	4.09	0.06	4.81	1.71	4.42	0.0
	G1038	1100	7.3	4.40	3.42	3.35	0.05	4.97	2.00	4.16	0.0
Shallaleh	J3010-S7EP1	1206	8.5	3.05	3.75	5.39	0.20	5.20	3.31	3.85	4.5
	S7-EP2	1203	7.3	3.10	4.17	3.75	0.33	4.60	1.13	5.13	0.8
Hammad	H1001	1680	0.0	7.80	3.42	6.39	0.13	5.34	6.92	4.47	0.0
	H1055	3200	0.0	10.00	9.25	13.57	0.43	14.23	14.92	3.50	0.0
	H2006	1860	0.0	5.25	5.00	8.52	0.18	8.26	6.13	3.92	0.0
	H1022	1643	0.0	4.00	4.83	7.52	0.23	8.00	4.63	3.66	0.0
	H2011	2600	0.0	7.40	7.58	11.21	0.30	13.10	10.69	3.63	0.0
	H1072	2620	0.0	8.35	6.67	11.22	0.48	10.14	11.42	4.76	0.0

Continued

Sirhan	J3011-S7EPII	1286	8.4	3.10	4.17	3.34	0.33	4.60	3.13	3.45	0.0
	J3016-S10EPII	1120	0.0	4.10	3.33	3.93	0.475	4.54	2.44	4.15	0.0
	J3004-S4OB	1500	8.1	6.00	3.32	6.30	0.225	7.14	4.90	3.18	0.0
	J3014-EPII	1290	7.6	5.02	2.33	5.96	0.125	5.49	2.54	3.95	0.0

(b)

	EC	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	NO_3
EC	1									
pH	−0.39251	1								
Ca	0.629092	−0.38121	1							
Mg	0.609597	−0.62644	0.674112	1						
Na	0.688547	−0.38254	0.691658	0.624726	1					
K	0.51705	−0.38946	0.439954	0.65609	0.508022	1				
Cl	0.720983	−0.47582	0.686603	0.757617	0.781671	0.392697	1			
SO_4	0.747099	−0.55053	0.836297	0.786504	0.861779	0.596814	0.844168	1		
HCO_3	−0.07149	0.117955	0.237808	0.173723	−0.24663	0.059742	−0.12353	−0.0423	1	
NO_3	−0.13306	0.221633	−0.14504	−0.29505	−0.12644	−0.20116	−0.06591	−0.26563	−0.06268	1

(c)

Area/Well Name/Code		Anhydrite	Aragonite	Calcite	Dolomite	Gypsum	Halite
Yarmouk	AD1208	−1.9838	0.2353	0.3791	0.5722	−1.7469	−6.0492
Azraq	F1274	−1.4901	0.2353	0.3827	0.5838	−1.2533	−6.0218
	F1045	−1.8394	0.1254	0.2729	0.6132	−1.6024	−5.9317
	F1013	−1.4791	−0.1485	−0.0604	−1.2423	−1.2423	−6.0792
Jafr	G1280	−1.9517	0.0611	0.2085	0.4487	−1.7147	−6.4039
	G1276	−1.9857	0.2346	0.382	0.763	−1.7487	−6.3571
	GL004	−1.9842	−0.0244	0.123	0.2413	−1.7472	−6.3488
Shallaleh	J3010-S7-EP1	−2.7863	−0.1658	−0.0184	1.1198	−2.5493	−0.2001
	S7-EP2	−2.2559	−0.1569	−0.0095	0.1735	−2.0189	−6.4935
Hammad	H1001	−1.2044	0.0001	0.1476	−0.0024	−0.9675	−4.9641
	H1055	0.9111	0.2114	0.3588	0.7059	−0.6746	−5.4564
	H2011	−1.6214	−0.977	−0.0503	0.0437	−1.3845	−5.4718
	H1072	−1.0756	0.2644	0.4118	0.7874	−0.8389	−5.6094
Sirhan	J3011-S7EPII	−2.2516	0.7434	0.8909	1.9781	−2.0146	−6.4904
	J3016-S10EPII	−1.8389	0.2538	0.4012	1.0151	−1.6019	−6.5187
	J3004-S4OB	−1.4214	0.6484	0.7958	1.4523	−1.1844	−6.0466
	J3014-EPII	−1.7109	0.2389	0.3836	0.488	−1.474	−6.174

The salinity of the water ranges from less than 1000 to 2700 μS/cm (only Hammad, H1055 has an EC of 3200 μS/cm (Table 6(a)). The water composition of all samples plots in the Piper diagram in the earth alkaline type with increasing portions of alkalis (Figures 6(a)-(c)). However, in Jafr Surroundings, Sirhan, and Yarmouk, the water shows only very slightly prevailing sulfates and chloride (Cl + SO_4 ≈ 55% - 70% of the anions and Ca + Mg ≈ 50% - 80% of the cations) relative to Azraq and Hammad groundwaters, which show strongly prevailing sulfates and chlorides (Cl + SO_4 > 75% of the anions and Ca + Mg ≈ 30% - 60% of the cations).

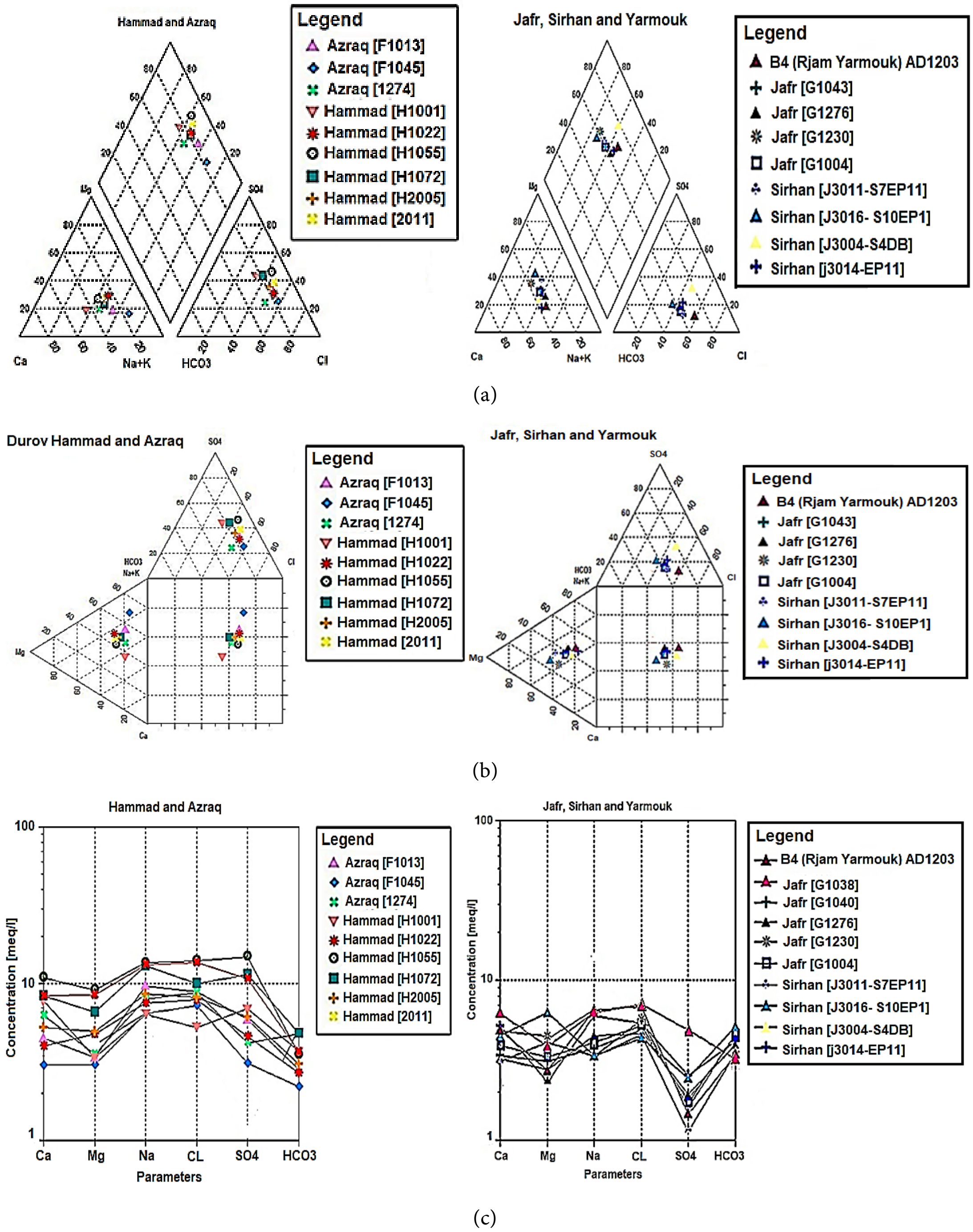


Figure 6. (a) The Piper diagram of the water in the Chalk Marl Formations; B4/5 (Rijam and Shallala) and the Sandstone Formation; B6 (Um Qirma in Azraq area), the basalt aquifer and the recent sediments of the highlands; (b) The Durov diagram of the water in the Chalk Marl Formations; B4/5 (Rijam and Shallala) and the Sandstone Formation; B6 (Um Qirma in Azraq area), the basalt aquifer and the recent sediments of the highlands; (c) The Schoeller diagram of the water in the Chalk Marl Formations; B4/5 (Rijam and Shallala) and the Sandstone Formation; B6 (Um Qirma in Azraq area), the basalt aquifer and the recent sediments of the highlands.

In the Durov diagram, all the water plots on the evaporation/dissolution line or very close to it, which indicates the absence or minimal presence of ion exchange processes.

Although the composition of this composite aquifer groundwater plots in the different diagrams in the same classification type, it shows important differences within these plots.

- Azraq and Hammad groundwater generally shows high salinities compared with Jafr Surroundings, Sirhan, and Yarmouk groundwaters.
- Jafr Surroundings, Sirhan, and Yarmouk groundwater plots in the Piper diagram are in the area of earth alkaline water with increased portions of alkalis and some sulfates, whereas in Azraq and Hammad, sulfates and chlorides strongly prevail.
- Jafr Surroundings, Sirhan, and Yarmouk water show ionic ratios of Ca ≈ Na > Mg and Cl > HCO_3 > SO_4, whereas that of Hammad and Azraq shows Na ≥ Ca > Mg and Cl > SO_4 > HCO_3, reflecting the effects of strong evaporation from playa and mudflat environments, leading to the higher concentrations of the groundwater on evaporates and eventual precipitation of gypsum.

5. Summary of Findings

Two main porous and permeable rock sequences of Upper Cretaceous to recent ages form the surface and near-surface aquifer systems in Jordan. These are: 1) the lower aquifer system of the combined Massive Limestone (A7) and Silicified Limestone (B2), together (A7/B2) composite aquifer, and 2) the Chalk Marl (B4,5), basalt, and recent deposits aquifer system; surficial aquifer. The thick Bituminous Marl Formation (B3) hydraulically separates these aquifer systems.

The A7/B2 receives recharge from precipitation and floodwater along its outcrops in the mountain areas overlooking the Rift Valley and their eastern plateau. Part of that recharge water issues in the form of freshwater springs and seepages along the highlands. The other part flows as a groundwater current towards the east, to where the Bituminous Marl Formation confines the aquifer and the groundwater comes under a reduced environment, and its salinity increases.

The unconfined part of the aquifer contains fresh water with low salinity (500 - 1000 μS/cm). Along the flow direction, in the confined part, the salinity increases gradually to more than 1000 μS/cm because of water-rock interactions, especially the interaction with the bituminous marls and the release of gases such as CO_2 and HS. In addition, the increase in groundwater temperature to more than 40˚C enhances the dissolution processes of the rock matrix.

The B4,5 basalt, recent sediments aquifer system receives recharge from precipitation water falling over its outcrops. The groundwater here shows low salinity of up to 1000 μS/cm, as is the case in Yarmouk, Sirhan, and the surroundings of Jafr Depression (erosion areas). However, in areas where playa sediments have formed, in Azraq, Hammad, and Central Jafr, the evaporates of the playa sediments affect the composite surficial aquifer by horizontal and vertical water-water interactions, and the groundwater salinity increases, and its type changes to chloride-sulfate from bicarbonate water.

6. Conclusion

The results and discussion allow us to conclude the following:

- Overexploitation of the directly recharged unconfined A7/B2 aquifer will lead to a reduction in the aquifer spring discharges and the amount of groundwater flowing towards the confined parts of the aquifer underlying the plateau area.
- Overexploitation of the confined part of the A7/B2 will lead, in a few tens of years, also to reductions in spring discharges in the unconfined and confined parts of the aquifer and the enhancement of releases of oil shale gases and minerals into the aquifer's groundwater, which may render that water unsuitable for household uses.
- Overexploitation of the directly recharged surficial aquifer B4,5, basalt, and recent sediments will result in reduced spring discharges, declining groundwater levels, enhanced entry of pollutants into the aquifer, and mobilization of salty groundwater underlying and surrounding playa areas, which will encroach into the fresh groundwater regimes. That applies especially to Azraq and Hammad areas and the immediate surroundings of the Jafr Depression (10-15 km from its center).
- Climate changes, reflected worldwide in temperature increase and in Jordan, additionally, in precipitation decrease, will certainly accelerate the aquifers water quality degradation and the groundwater yields.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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